VSM (Virtual Synchronous Machine) Power Quality, Harmonic and Imbalance Performance, Design and Service Prioritisation

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***Abstract*— System level studies have shown that the use of Grid Forming control schemes such as the Virtual Synchronous Machine (VSM) for grid connected power electronic convertors may offer significant benefits to increasing the penetration of convertor based distributed generation [5]. However, the VSM control scheme inherently makes the convertor system operate in a voltage controlled, rather than a current controlled mode and this makes it susceptible to disturbances on the grid. This paper will investigate this phenomenon when harmonics and imbalance are present on the grid supply.**

***Keywords*— Grid Forming Convertors (GFC), Virtual Synchronous Machine (VSM), GC0100, Grid Codes, Inertia, Harmonics, Imbalance**

I. Introduction

This paper is the fifth of five papers describing National Grid's VSM (Virtual Synchronous Machine) NIA (Network Innovation Allowance) projects. These two projects have been undertaken in partnership with University of Nottingham (UoN) and University of Strathclyde (UoS). They are intended to improve the understanding of the implications of Grid Forming Convertor (GFC) proposals addressed through GC0100 Option 1 [7] and subsequently the VSM Expert Group [6]. The purpose of the projects and/or papers are:

1. To design and test a VSM algorithm in line with general GFC/VSM principals such as GC0100 option 1 [7].
2. To establish which plant control principals, parameters and tests are particularly relevant to grid stability.
3. To understand how grid forming performance affects one of the possible convertor designs and strategies which might mitigate any negative effects.
4. To establish whether it is possible to provide grid forming performance from hybrid solutions (for example STATCOMS) where not all of the converters are grid forming.

It should be noted that whilst the authors have sought to explore a possible implementation of VSM, it is not National Grid's intention to mandate any specific design. NG ESO (National Grid Electricity System Operator) only seeks to examine some of the practical considerations surrounding the technical requirements detailed in [6] and [7]. This is not intended to prescribe a design of a physical convertor, it is intended to simply illustrate one potential approach for discussion though it is noted that some other implementations could be used some of which are also discussed in the papers.

It is suggested readers first read [1] to get a broader introduction conclusions on the topics and controller models presented in this paper and the other paper.

Table 1 below, shows a matrix of future anticipated GB transmission system, convertor growth inhibiters in the columns and the potential counter measures in the rows. The cells which intersect the columns and rows, show which counter measures are capable of resolving the various inhibiters.

Solution	Estimated Cost	RoCoF [1] [2]	Sync Torque/Power (Voltage Stability/Ref) [2] [3] [4]	Prevent Voltage Collapse [2]	Prevent Sub-Sync Osc. / SG Compitable [2] [3]	Hi Freq Stability [2]	RMS Modelling [1] [2] [3] [4]	Fault Level [1] [2]	Post Fault Over Volts [2]	Harmonic & Imbalance [*]	System Level Maturity	Notes
Constrain Asyncronous Generation	Hgh	I	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Proven	These technologies are or have the potential to be Grid Forming / Option 1
Syncronous Compensation or more Sync Gens at lower load	High	I	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Proven	
VSM	Medium	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	P	Modelled	
VSM0H	Low	No	Yes	Yes	No	P	P	P	Yes	P	Modelled	Has the potential to contribute but relies on the above Solutions
Synthetic Inertia	Medium	Yes	No	No	P	No	No	No	No	No	Modelled	
Other NG Projects	Low	Yes	P	Yes	No	No	No	P	P	No	Theoretical	

Key

No	Doesn't Resolve Issue
P	Potential
I	Improves
Yes	Resolves Issue

Table 1 – Future System Problems and Solutions

It can be seen from Table 1 that only three counter measures are believed to be holistic, potentially solving all/most of the anticipated inhibiters, either on their own or in combination. This does not mean that the other counter measures investigated are not useful but would need to be combined with other solutions which uniquely solve other areas which are increasingly influencing the practical costs in the operation and planning of networks.

Figure 1 below shows the overall block diagrams of the controllers implemented by NG ESOs partners UoN and UoS. The implementation of the controllers and associated hardware differ slightly as each partner focused on different aspects of the design but both are similar implementations and are discussed in the relevant papers. In addition to the physical implementation and realization of the convertors both partners and NG have built models in MATLAB, RTDS and RMS models in PF (PowerFactory). The numbers [2] [4] etc. in

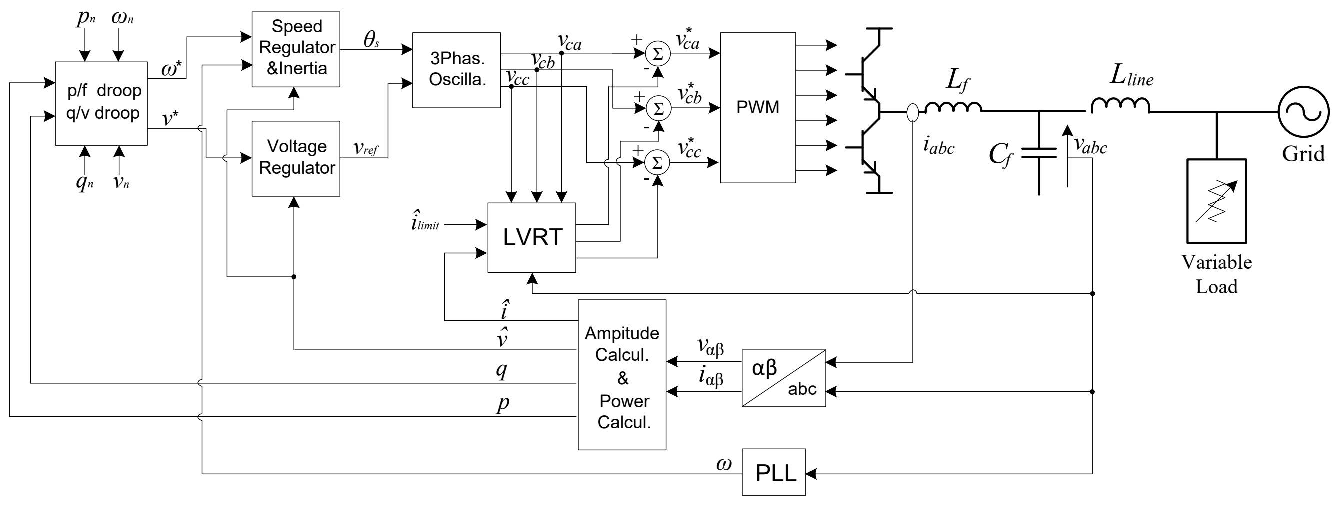

Figure.2. Schematic of the Central VSM Controller.

Figure 1 indicate where specific topics are covered by specific papers and [*] refers to this paper.

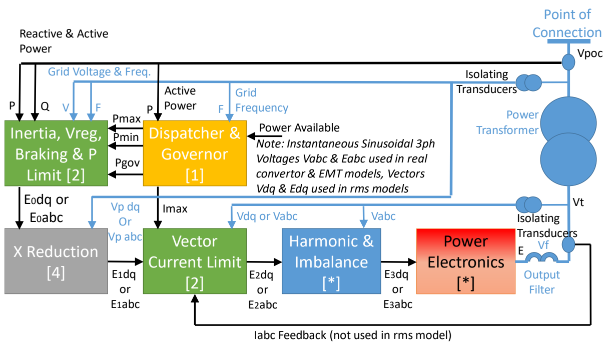

Figure 1 – Simplified Block Diagram of a potential VSM Implementation

From Figure 1 we can see the converter design largely consists of six major blocks:

i) Dispatcher and Governor

ii) VSM (Inertia simulation and stabilizing, Dynamic braking, Voltage Control and Power Limiter).

iii) Impedance Reducer

iv) Vector Current limiter

v) Harmonic and Imbalance Management

vi) Convertor Output Stage and Power Electronics

This paper focuses on v) and vi), the influences of system harmonics and imbalance on the operation of the power electronic convertor. The VSM control scheme inherently makes the convertor system operate in a voltage controlled, rather than a current controlled mode and this makes it susceptible to disturbances on the grid. This paper will investigate this phenomenon when harmonics and imbalance are present on the grid supply. Section II will provide a brief overview of the central VSM algorithm used in this work, with section III illustrating the challenges introduced by harmonics and imbalance contained in the grid voltage. Section IV introduces a simple mechanism for mitigating the harmonic disturbances, and validates this scheme experimentally. Sections V and VI discuss the implications of these harmonics on convertor design and operation, and propose a mechanism for exploiting any available (residual) current capability from the convertor to provide harmonic compensation, when appropriate.

II. The Virtual Synchronous Machine Control Algorithm

Fig.2 shows the system schematic for the central VSM controller implemented in this work [2]. The outer control incorporates two droop controllers – one for power/frequency (P/F) and one for reactive power/voltage (Q/V). These droop controllers compare reference settings with measurements of real and reactive power to determine set-points for the inner regulators which control the frequency (speed) and amplitude of the converter output voltage. The droop functions can be expressed as (1)-(2):

$$\omega^* = \omega_n - m_p(P - P_n) \tag{1}$$
$$V^* = V_n - m_q(Q - Q_n) \tag{2}$$

where $P_n$and Q_n, ω_n and V_n are the nominal real and reactive power and the nominal system frequency and voltage. ω^* and V^* are the frequency and voltage references and m_p and m_q are the droop gains. The frequency and voltage amplitude controllers determine the phase (referred to the active power vector) and the amplitude of the desired output voltage of the power converter and pulse-width modulation is used to drive the converter switches and create the actual three phase voltage at the inverter output.

Fig. 3 shows the speed regulator system which comprises a speed governor, a function typically emulating the behaviour of a prime mover (in this case an ignition delay term), and a function representing the desired inertia of the VSM. The governor and prime mover are implemented as a proportional-integral (PI) controller and a first-order lag element with time-constant, T_{en}, respectively. The model of the synchronous machine is simplified using the typical swing equation defined as (3):

$$T_m - T_e = J\frac{d\omega}{dt} + D_m(\omega - \omega^*) \tag{3}$$

where T_m , T_e, J, ω are the mechanical torque, the electrical torque, moment of inertia, and grid frequency. Note that the schematic of Fig. 2. includes a brake switch which has the equivalent effect of near perfect braking resistors on a conventional synchronous generator, preventing the equivalent of rotor acceleration for fault voltages of less than 0.85pu. It is necessary to prevent power swings following a fault which might exceed rated values. The removal of these swings also benefits the power system as a whole, removing disturbance and any resulting interactions.

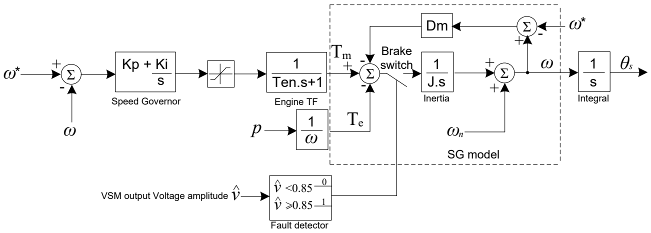

Fig.3. Block diagram of speed regulator

Fig. 4 shows the voltage regulator system which comprises a PI controller, and functions emulating the behaviour of the generator's field circuit [2]. The time constant (*Td*) is set to 31ms or greater e.g. 10s it acts as a low pass filter blocking signals above 5Hz and reduces the risk of electromechanical interactions with mechanical shaft resonant frequencies on nearby synchronous generators. Likewise, the inertia time constant J.s and 1st order lag time constant *Ten* are set to block signals above 5Hz, preventing them from modulating the frequency, angle and power. This is a requirement of GC0100 option 1 [2, 7] which states that the convertor should operate as a voltages source over the 5Hz to 1kHz band.

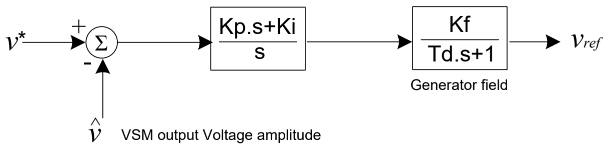

Fig. 4. Block diagram of voltage regulator

The VSM controlled system must operate correctly when the power system operates in abnormal conditions e.g. during system fault conditions. Note that in the control schematic of Fig. 3 there is no direct control of the converter current and this parameter can potentially exceed rated values. The central VSM controller has therefore been supplemented by two further control loops to address abnormal operating modes – the power limit control (which helps the VSM system continue to contribute to system operation during abnormal conditions) and the current limit control (which protects the power converter itself without disconnecting it from the grid). These two modes of operation are not described here as they are the focus of an accompanying paper [2].

In this controller design, a PWM switching frequency of 2kHz is used. This ensures the output voltage on each phase is updated 2000 times a second and the maximum bandwidth is theoretically 1kHz, meeting the GC0100 option 1 requirement for the voltage source bandwidth. Furthermore, both switching edges of the PWM are controlled and this results in 4000 updates per second and a higher bandwidth than 1kHz.

III. The Challenges of Grid Power Quality on VSM Behaviour

An important factor when designing the VSM control is to limit the dynamic response of the system and make it comparable with a conventional synchronous generator. The VSM converter is therefore susceptible to fast changes in the power system, and the presence of harmonics or unbalance in the grid supply voltage at the point of connection will result in the presence of significant harmonic or unbalanced currents drawn from the VSM converter. This susceptibility will now be illustrated. The proposed VSM algorithm has been used to control an experimental 15kVA battery energy storage system (BESS) – described in the Appendix. The BESS can be interfaced to the local distribution grid (supplied to the lab from a 1MVA transformer), or to a Triphase PM90F30F42 90kVA programmable three phase, four wire source. In the first instance, the converter is connected to the local distribution grid and controlled to deliver 4kW to the system. The converter currents are shown in Fig. 5. It can clearly be seen that these are dominated by 5th and 7th harmonics, even though the outer droop controllers are requesting fundamental power delivery only. Table 2 lists the harmonic content of the local distribution grid and it is clear that the grid harmonics are the source of most of the harmonics present. The inverter current harmonics are listed in Table 3. for this test scenario.

	Fundamental	**3th**	**5th**	**7th**
Va	325.15	0.68 (0.2%)	6.1 (1.8%)	2.65 (0.8%)
Vb	325.29	0.15	6.3	2.63
Vc	325.35	0.35	5.7	2.66

Table 2. Harmonic Content of the local distribution grid voltage.

	Fundamental	**3th**	**5th**	**7th**
Ia	5.88	0.1	1.57	0.55
Ib	6.7	0.2	1.56	0.59
Ic	5.97	0.1	1.45	0.55

Table 3. Harmonic Content of the converter currents when connected to the local distribution grid.

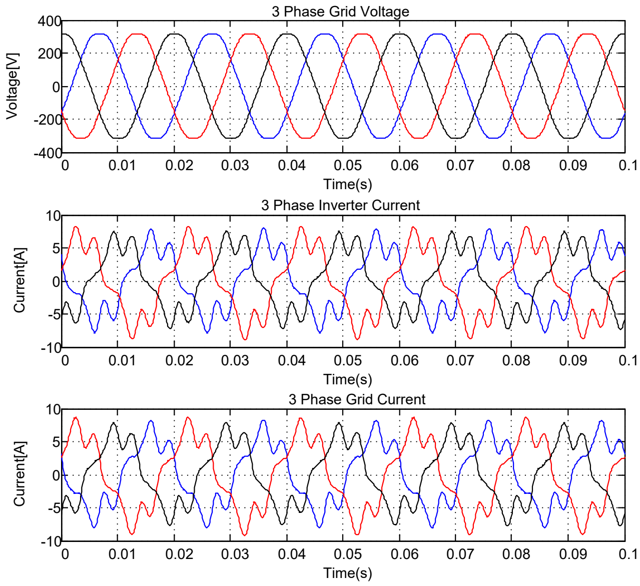

Figure 5. Current Drawn by VSM System when connected to local distribution grid

It is clear that when operating from the grid the VSM system draws a significant 5th and 7th harmonic current due to the harmonics contained in the supply voltage, and the three fundamental currents are also unbalanced due to imbalance between the three supply phases.

For the second test scenario, the same VSM system was connected to the 90kVA programmable supply with an (almost) ideal supply waveform as shown in Fig. 6. It can be clearly seen that the VSM controlled BESS is controlling near sinusoidal currents and that the distortion seen in Fig. 5. is due mainly to the harmonic content of the local supply voltage, and the VSM algorithm makes the power converter "susceptible" to these local harmonics: their amplitude is limited mainly by the impedance of the filter connecting the power converter to the grid. However, in the context of grid support, the ability of the convertor to absorb some harmonic current can useful in order to actively clean up the voltage waveform, as long as they do not cause the convertor to exceed its rated values.

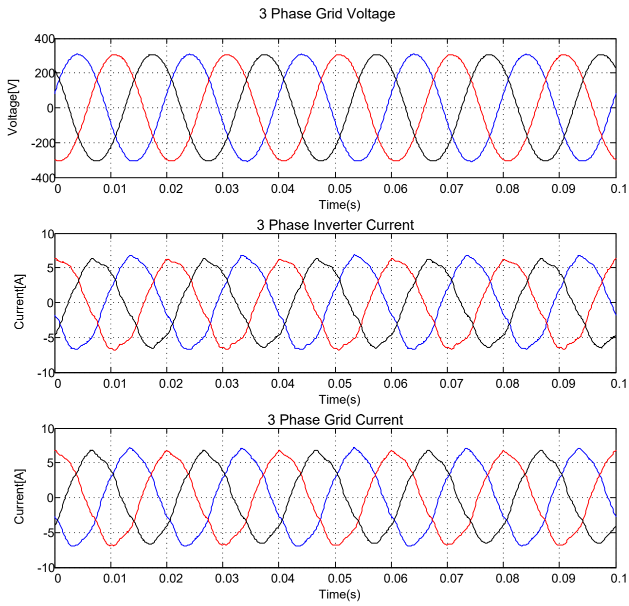

Figure 6. Current Drawn by VSM System when connected to the 90kVA programmable voltage supply

IV. Compensation for Local Voltage Harmonics

It is usually desirable to remove the harmonic content from the inverter current, as when it is operating at near to rated power, the harmonic currents will cause additional losses within the converter which then can cause overheating and failure of power electronic devices (this will be discussed later in the paper). It is possible to introduce a simple compensation scheme which can help the converter reject the harmonic disturbance from the grid. For this work a high-pass filter was created to remove the fundamental component from the measured grid voltages. This residual voltage (V_{abcHPF}) can then be added to the inverter reference voltages (from the main VSM controller) and these "oppose" the harmonic voltages in the grid to prevent harmonic currents being drawn by the convertor. For this work the high-pass filter has been created in a rotating reference frame using a "synchronous filter" [16] as shown in Fig. 7.

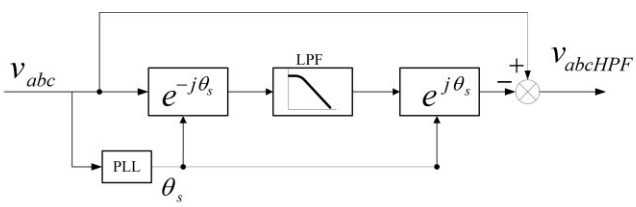

Figure 7. Compensation Scheme for Removing Harmonic Currents.

A reference frame synchronised to the main grid voltage is created using a (relatively slow) phase locked loop which generates a grid synchronizing reference angle θ_s. The measured grid voltages (V_{abc}) are transformed to this reference frame using θ_s and passed through a low pass filter with cut of frequency 1.5Hz. The output of this is then transformed back to the stationary reference frame and subtracted from the original voltage. The net effect is for the system to behave as a high pass filter – the remaining voltage V_{abcHPF} represents the harmonic voltages present in the grid, which can be added to the inverter reference voltages from the main VSM controller (V_{ca}*, V_{cb}* and V_{cc}* in Fig. 2). This arrangement allows us to implement harmonic compensation with a simple filter arrangement, and also has the ability to follow grid frequency changes. Other approaches can be used in the stationary reference frame if a PLL is to be avoided. The filter has a relatively low dynamic response, but at the same time can provide very good harmonic rejection.

To demonstrate the performance of the compensation scheme the BESS was connected to the local grid supply and controlled to deliver 4kW to the grid. The supply voltage, inverter and grid currents are shown in Fig. 8. The harmonic content of the grid voltage and inverter current are given in Tables 4 and 5.

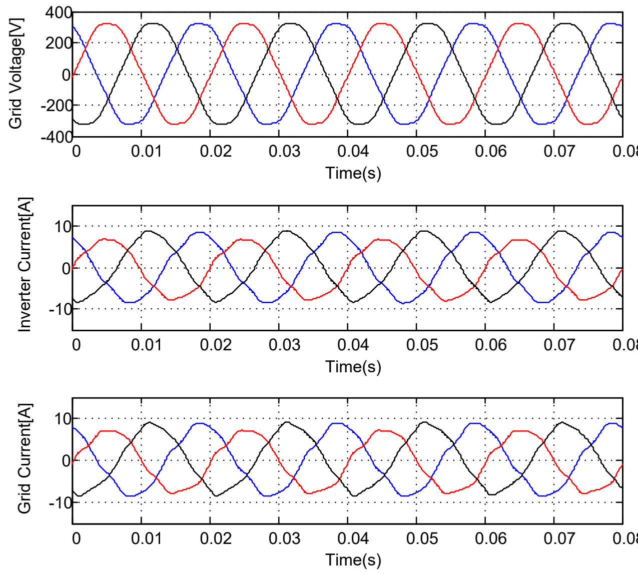

Figure 8. Current Drawn by VSM System when connected to local distribution grid, and employing the proposed harmonic compensation scheme.

	Fundamental	3th	5th	7th
Va	331.31	0.98 (0.3%)	8.63 (2.6%)	1.86 (0.6%)
Vb	329.69	0.78	8.71	1.71
Vc	331.55	0.44	8.15	1.67

Table 4. Harmonic Content of the local distribution grid voltage when employing the proposed harmonic compensation scheme.

	Fundamental	3th	5th	7th
Ia	8.3	0.25	0.29	0.08
Ib	7.37	0.27	0.33	0.14
Ic	8.16	0.24	0.23	0.13

Table 5. Harmonic Content of the converter currents when connected to the local distribution grid and employing the proposed harmonic compensation scheme.

V. Additional Considerations

It has been shown that the harmonic content of the local grid voltage will create harmonic current in the VSM controlled convertor, and this will increase the rms current of the converter and associated power losses for a given level of desired power (or reactive) transfer. It will therefore lead to a de-rating of the power capability. There are however further effects within the VSM converter. If the active power delivered from the experimental BESS is calculated, it is seen to contain a high degree of oscillation as seen in Figure 9.a. The main frequency seen here is 300Hz (resulting from both the 5th and 7th harmonic components), and the oscillation has an amplitude of 1.1kW (noting the DC power level is 4kW). This will transfer to a power oscillation seen on the both the DC link of the power converter (seen Fig. 9.b), and the actual current drawn from the battery (see Fig. 9.c). These oscillations will have a serious impact on component lifetime, particularly the DC link capacitor and the battery itself. These oscillations could be reduced by a significant increase in the DC link capacitor size, or a mixture of capacitor technologies (e.g. by using film technology), but this would obviously increase size and/or cost of the convertor system.

When the harmonic compensation is employed, the resultant effect on the power transfer, DC link voltage and battery current are shown in Fig. 10. There is a significant reduction in the harmonic content of the power waveform – the removal of the components at 300Hz. The remaining oscillations (at 100Hz) result from unbalance present in the supply voltage: this cannot be addressed unless a further degree of control is introduced into the system e.g. a connection between the supply neutral and the DC link capacitor midpoint, or the introduction of a 4th inverter leg connected to the supply neutral. Both solutions have disadvantages associated with them and will be explored as future work. It should also be noted that most distribution system level transformers have a star-delta connection reducing the zero sequence (unbalance) components.

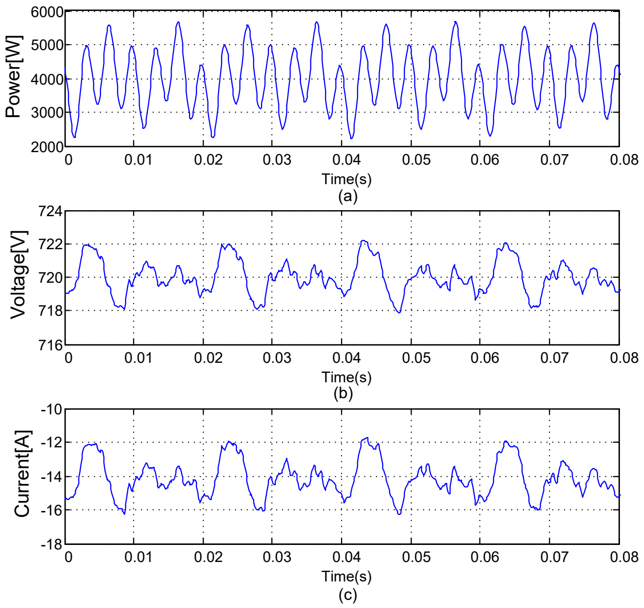

Figure 9. a) Active Power Delivered by the BESS when Operating without Harmonic Compensation. b) DC Link Voltage of the Power Converter c) Battery Current of BESS

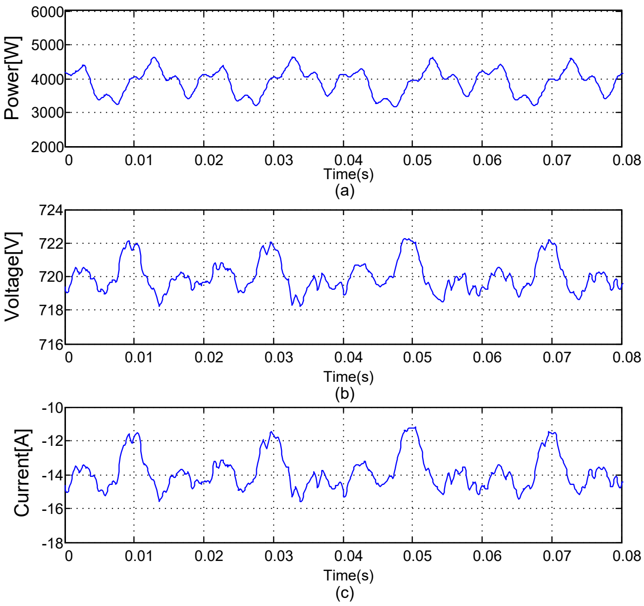

Figure 10. a) Active Power Delivered by the BESS when Operating with Harmonic Compensation. b) DC Link Voltage of the Power Converter c) Battery Current of BESS

VI. DISCUSSION

The VSM algorithm controls the power convertor as a voltage source. There are other approaches to creating a grid forming convertor [9-11], some of which employ an inner current loop. The current controllers, whether executed as a Proportional plus Integral controller in the synchronous DQ reference frame, or as stationary resonant controllers, require a high bandwidth PLL and this has been shown to reduce the robustness of the control to grid disturbances [5]. However, the current loop will ensure that the convertor can reject the harmonic content of the grid and therefore reduce the inverter power and DC link voltage oscillations inherently. Specific control of unbalanced currents can be incorporated by employing a 4th inverter leg connected to the supply neutral [12].

There has been much work undertaken recently to mitigate reactive power, harmonics and unbalance in inverter dominated microgrids which employ grid following convertors (employing a high bandwidth current loop) [17, 18]. The aim here is to use any residual capability from the convertor at a specific operating condition, to help to reduce the harmonic or imbalance content of the grid. The term "Residual Capability" in this context means the difference in RMS current between the currently delivered active power from the convertor, and its sustainable rated RMS current. Recent work undertaken by the authors for example [13] has employed the Conservative Power Theory (CPT) to extract specific components for active, reactive, unbalanced and void (harmonic) currents in the power system and use these as references directly within the convertor control. Other approaches have been developed, for example the Instantaneous Reactive Power Theory [14], for extracting and controlling non-active fundamental current components.

Fig. 11. Illustrates the basic principle of the approach proposed in [15]. The CPT algorithm uses measurements of line voltage and current to determine the active fundamental, reactive fundamental, unbalanced and void components of the three phase currents: the components for phase a only are shown in Fig. 11 – I_{aa}, I_{ar}, I_{au} and I_{av}. These can then be used as part of a feedback control system to try to mitigate these components in the grid current and concepts such as virtual impedance can be used to limit the individual currents in a particular convertor or share these components between different convertors. Fig. 11. Shows a simple approach (for phase a only for simplicity) whereby the gains K_{ar}, K_{au} and K_{av} are used to control the levels of the reactive, unbalanced and void components, and can be adjusted "on-the-fly" to suit the specific operating conditions of the convertor. V'_a is the final reference voltage sent to the convertor's PWM modulator.

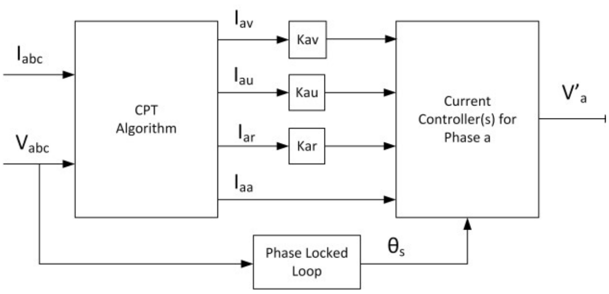

Fig. 11. The use of CPT to Specifically Control Levels of Current Absorbed by the Convertor when a Current Control Loop is Used.

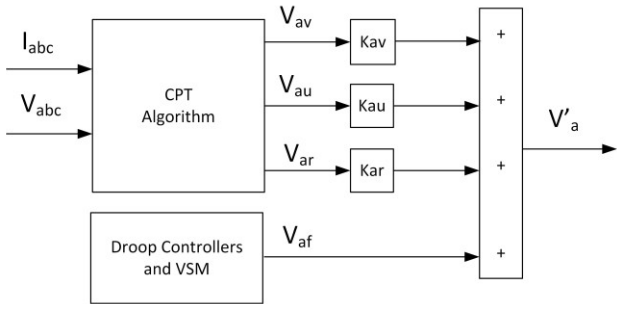

Fig. 12. The use of CPT to Specifically Control Levels of Current Absorbed by the Convertor when VSM is used.

A similar approach can potentially be adopted for the VSM algorithm as illustrated in Fig. 12. In this case the grid voltage, rather than the current is decomposed into reactive, unbalanced and void (harmonic) components V_{ar}, V_{au} and V_{av}, and these values can be added to the fundamental active voltage (V_{aa}) derived from the VSM algorithm itself prevent these components appearing in the convertor current. Again, gains can be used to adjust these reference values to allow the convertor to draw harmonic or unbalanced current in a controlled way (shown for phase a only), to provide some grid support for these conditions if the convertor is operated below its rated power level. In this case the harmonic current absorbed by the convertor is controlled as a proportion of the residual capability by directly controlling the amplitude of the void compensation voltage shown in Fig. 12.

The control structures illustrated by Figs. 11 and 12 demonstrate that both grid forming and grid following convertors can offer support for harmonic and unbalance mitigation when they are not operating at rated RMS current. Harmonic compensation is generally a concern in steady-state conditions and therefore harmonic compensation should be considered a lower priority than dynamic capabilities such as fault ride through or frequency support. Also, harmonic compensation can potentially be a capability for which the convertor operator receives reward, and can therefore become a significant part of the development of future grid codes. ENTSO-E TG HP draft Technical Report [19] includes a

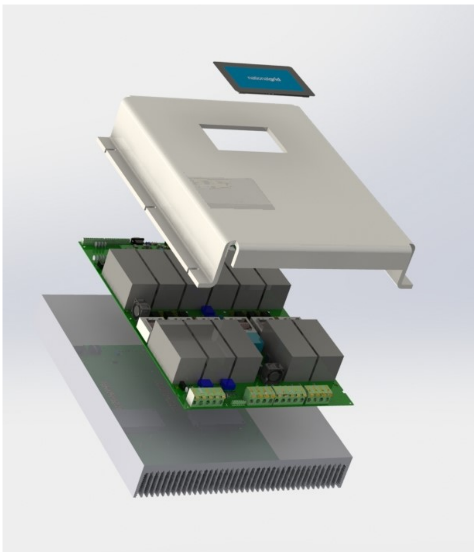

Fig 13. Prototype VSM Convertor

discussion of this aspect of convertor based distributed generation.

The authors in collaboration with TTPi Ltd have developed a prototype 15kW VSM convertor interface for a battery energy system, as shown in Fig. 13. This design is easily be replicated if interested parties want to evaluate a VSM system in an experimental environment.

VII. Conclusions

This paper has presented findings from an experimental implementation of the Virtual Synchronous Machine algorithm within a grid connected environment. Results presented demonstrate that the VSM convertor control will make the system susceptible to the harmonic and unbalance content of the grid voltage and the harmonic currents drawn by the convertor can be very significant. These harmonics also have a significant effect of the convertor's DC link voltage and this may have a detrimental effect on the DC link capacitor of the convertor, and also the power source itself (particularly for example if it is a lithium ion battery or fuel cell). Mitigation of unbalance requires convertor modifications, for example the incorporation of a 4^{th} inverter leg connected to the supply neutral. However, a harmonic compensator has been proposed which employs a high pass filter and this has been shown to reduce the harmonic currents drawn from a distorted grid. This control has been discussed in relation to grid services, whereby the ability to use "Residual Capability" of a convertor for mitigation of harmonics or unbalance, may be rewarded.

Acknowledgment

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Appendix

The experimental system comprises a 24kWh lithium Ion battery connected to the supply using a 15kVA Triphase_PM15F42C_15kWpower converter. The converter provides both a three-phase DC-AC inverter and a DC-DC converter to interface the battery to the inverter's DC link. The control of both converters is implemented in an embedded PC to provide a flexible software/algorithm development system, using the Matlab/Simulink environment. The local supply is provided either by a 1MVA transformer connected to the local medium voltage network, or using a 90kVA Triphase PM90F30F42 programmable voltage supply.

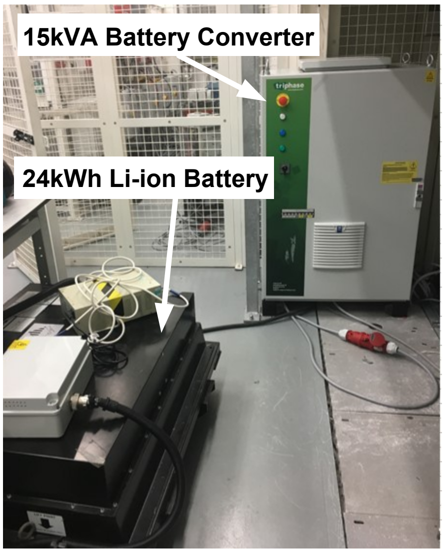

Fig. A.1 Experimental VSM System

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